Near-Infrared-Spectroscopy with Extremely Large Telescopes: Integral-Field- versus Multi-Object-Instruments

F. Eisenhauer, M. Tecza, N. Thatte, S. Mengel, R. Hofmann and R. Genzel

Max-Planck-Institut für extraterrestrische Physik, P.O.Box 1603, 85740 Garching, Germany

ABSTRACT

Integral-field-spectroscopy and multi-object-spectroscopy provide the high multiplex gain required for efficient use of the upcoming generation of extremely large telescopes. We present instrument developments and designs for both concepts, and how these designs can be applied to cryogenic near-infrared instrumentation. Specifically, the fiber-based concept stands out the possibility to expand it to any number of image points, and its modularity predestines it to become the new concept for multi-field-spectroscopy. Which of the three concepts — integral-field-, multi-object-, or multi-field-spectroscopy — is best suited for the largest telescopes is discussed considering the size of the objects and their density on the sky.

Keywords: Near-Infrared-Spectroscopy, Integral-Field-Spectroscopy, Multi-Object-Spectroscopy, Multi-Field-Spectroscopy

1. Extremely Large Telescopes and Near-Infrared-Spectroscopy

1.1. Science with Extremely Large Telescopes

Extremely Large Telescopes[2,4,10,13] of the next century will have diameters of up to 100 m. Compared to current state of the art 10 m-class telescopes, the biggest of those telescopes provide a collecting power roughly 100 times as big, and an angular resolution 10 times as good. The science-drivers for such telescopes are threefold:

First, and most straight forward, we will be able to carry out spectroscopy of objects that we already know about from deep imaging, but which are too faint for spectroscopy with present day telescopes. The most prominent and cited target of such observations is the Hubble Deep Field.

Second, we will image objects that we have never seen before, because they are too faint or too distant.

These two science drivers are the straight forward extension of what astronomers have done during the last century, and at first sight seem related only to the collecting area of the telescopes. But since such observations will be background limited, we will only gain a factor of 10 — 2.5 magnitudes — compared to the existing 10 m telescopes for seeing limited observations of point sources. Only adaptive optics assisted observations at the diffraction limit of the telescopes will boost the limiting magnitude by a factor of 100 — 5 magnitudes — when enlarging the mirror-size from 10 m to 100 m. High angular resolution capability therefore will be mandatory.

And third, most exciting for us, is the prospect of exploring the universe at angular scales of a few milliarcseconds, the diffraction limit of such an Extremely Large Telescope. Like the Hubble Deep Field for the faint object science, the direct imaging and spectroscopy of planets can serve as the final goal for high angular resolution astronomy. While imaging at this angular resolution will also be possible with interferometric arrays like the VLT, only the collecting area of several 1000 m^2 will provide enough photons for spectroscopy.

1.2. The Need for Integral-Field- and Multi-Object-Instruments

Since an Extremely Large Telescope will cost the order of 1 billion US$, throughput of the instruments has highest priority. Throughput in this context does not only mean imperfect transmission and detection of the light, but specifically multiplex-gain. For the faint-object-science, best throughput implies simultaneous spectroscopy of as many objects as possible. This is the standard domain of multi-object-spectroscopy. On the other hand, if objects are to be resolved, and if we are interested in their complex structure, integral-field-spectroscopy is the the first choice. This technology is definitely required when observing with adaptive optics at the diffraction limit of a telescope, both to avoid imperfect slit-positioning on the object, and for post-observational correction of the imperfect point-spread-function by means of deconvolution.

1.3. Why Near-Infrared-Spectroscopy?

There are several reasons, both object-inherent and technical, to carry out a significant fraction of the observations with such a telescope at near-infrared wavelengths:

First, many of the faint objects we are looking for — like in the Hubble Deep Field — are at high redshift. Therefore a lot of the well established "optical" spectral diagnostics are shifted beyond 1 micron.

Second, many of the interesting objects in the universe — like nuclei of galaxies, star- and planet-forming regions — are hidden behind dust. For example our Galactic Center is dimmed in the visible by about 30 magnitudes, while we suffer from only 3 magnitudes of extinction in K-Band (2.2 μm).

And third, high angular resolution through the earth's atmosphere is much easier achieved at longer wavelengths. Even though there is no principle limit to achieve the diffraction limit in the visible, the high complexity of an adaptive optics system for an extremely large telescopes with roughly 10^5 actuators[4] may suggest to start with the easier task of correcting in the near-infrared.

2. Concepts for Integral-Field- and Multi-Object-Spectroscopy

In this section we will present current developments and concepts for integral-field-spectroscopy and multi-object-spectroscopy (with emphasis on the technology developed at the Max-Planck-Institut für extraterrestrische Physik), and outline the technology-challenge for their operation at cryogenic temperatures.

A number of instruments have been built or are going to be built for integral-field-spectroscopy and multi-object-spectroscopy. Even though most of them are designed for operation at visible wavelengths, their concepts are applicable for the near-infrared as well. In this section we will describe the basic idea behind the different approaches and compare their specific properties and feasibility at cryogenic temperatures.

2.1. Integral-Field-Spectroscopy

An integral-field-spectrograph obtains simultaneously the spectra for a two-dimensional field with a single exposure. It therefore distinguishes itself from several other ways of measuring spectra for a two-dimensional field, which all need multiple integrations. Well known and applied in astronomy for several decades are (1) Fabry-Perot-imaging-spectroscopy, (2) Fouriertransform-spectroscopy, (3) slit-scanning-spectroscopy. Why is integral-field-spectroscopy most appropriate to ground-based astronomy, especially at the highest angular resolution?

Fabry-Perot-imaging-spectroscopy and Fouriertransform-spectroscopy require repetitive integrations to obtain full spectra. Therefore ground-based observations suffer a lot from varying atmospheric conditions. Both atmospheric absorption and emission must be measured in between two adjacent wavelength-settings, and since the atmospheric properties vary on a time-scale of minutes at near-infrared-wavelengths, long single exposures, and therefore high quality spectra for faint objects are almost impossible to record with wavelength scanning techniques. The difference between integral-field-spectroscopy and slit-scanning is in principle rather small, since both instruments provide roughly the same number of image points and the same spectral sampling. But because most astronomical targets are far from being slit-like, almost all observations can gain a lot from a square field of view.

Three basic techniques are used in today's instruments for integral-field spectroscopy: The Mirror-Slicer, the Fiber-Slicer and the Micro-Pupil-Array.

The basic idea of image-slicing with mirrors is rather simple: A stack of tilted plane mirrors is placed in the focal plane, and each mirror reflects the light from the image in a different direction. At a distance at which the rays from the different mirrors are clearly separated, a second set of mirrors realigns the rays to form the long-slit (figure 1) of a long-slit-spectrograph, which disperses the light along the rows of the detector. This concept was successfully applied in the 3D-instrument,[5] a near-infrared integral-field-spectrometer developed and operated by MPE, and will be used for SPIFFI II, the adaptive-optics-assisted field-spectrometer for the VLT-instrument SINFONI[18,15] . The disadvantage of this concept is that shadowing at the steps of the first stack of mirrors leads to unavoidable light losses. This shadowing effect increases with smaller mirrors and a larger field of view. In order to have little light losses one would like to have large mirrors in the first stack. Because this increases the total slit-length, and therefore makes the collimator of the spectrograph-optics uncomfortably big, a compromise has to be found. For SPIFFI II with its approximately 1000 spatial pixels arranged in 32 slitlets, we chose the width of each mirror of the first stack to be 300 μm, which leads to a total slit-length of about 300 mm. For these parameters the shadowing-effect cuts out about 11% of the total light.[17] The whole slicer for SPIFFI II will be fabricated from Zerodur using classical polishing techniques. Optical contacting of the individual mirrors will provide a monolithic structure that is insensitive to changes in temperature. With 3D we proved that the concept is feasible, and our recent results from cool-downs of an engineering slicer to the temperature of liquid nitrogen ensures operation in cryogenic instruments. However, the concept will find its limitation for much larger fields due to increased shadowing. Other recent developments of mirror-slicers derive from the basic design with plane mirrors, and take advantage of curved mirrors.[3] Such a concept avoids part of the shadowing-effects and provides a smaller "slit", thereby simplifying the design of the spectrograph-optics.

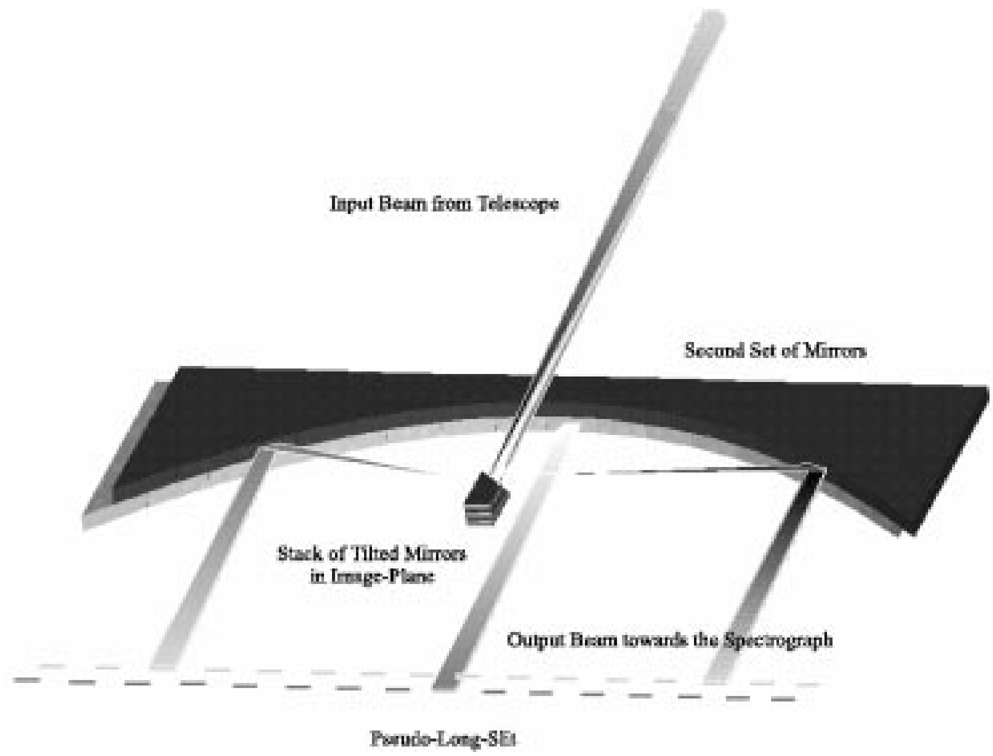

Figure 1. Image-slicing with mirrors: A stack of tilted plane mirrors is placed in the focal plane, and each mirror reflects the incoming light in a different direction. At a distance at which the rays from the different mirrors are clearly separated, a second set of mirrors realigns the rays to form the long-slit.

A completely different approach for integral-field-spectroscopy is based on optical fibers. In the image plane the two dimensional field is sampled by a bundle of optical fibers, which are then rearranged to a "long-slit". As in the mirror-slicer-concept, a normal long-slit spectrograph can be used to disperse the light. As simple and expandable as this concept seems, many little problems are inherent to such devices.

To achieve a high coupling-efficiency, an array of square or hexagonal lenslets with a filling factor of close to 100 % is used to couple the light into the fibers. However, for a high coupling efficiency the fibers have to be accurately positioned behind each lenslet and the image quality of the lenslets has to be very good. One way to loosen the constraints on the positioning accuracy and the optical quality of the lenslets is to use a larger $A\Omega$ for the fiber, which in turn increases the f-number of the spectrograph-camera and finally limits the pixel-size, especially at extremely large telescopes. For a cryogenic instrument the positioning of the fibers behind the lenslets is another critical point, since differential thermal contraction both complicates gluing of the lenslets and fibers, and due to small displacements degrades the coupling efficiency. For SPIFFI[16] we therefore started the development of monolithic lens-fiber-units (figure 2), each consisting of a silica-fiber, that has been flared and a spherical lens polished onto it.[17] Even though individual fiber-lens-units could be produced with an overall transmission of more than 70 % — including coupling efficiency, reflection losses and intrinsic absorption —, the technology is not yet optimized for producing several 1000 fibers at reasonable cost. Despite all the technical problems with the image-slicer based on flared fibers, there are three main advantages of this concept over its competitors: First, its possible extension to any number of fibers. Second, this concept provides full flexibility in the arrangement of the fibers (see section on multiple-field-spectroscopy). Third, the flared fiber is insensitive to a change in temperature and can be used at cryogenic temperatures. The flared-fiber technology will be implemented in LUCIFER,[9] the general-purpose near-infrared instrument for the LBT.

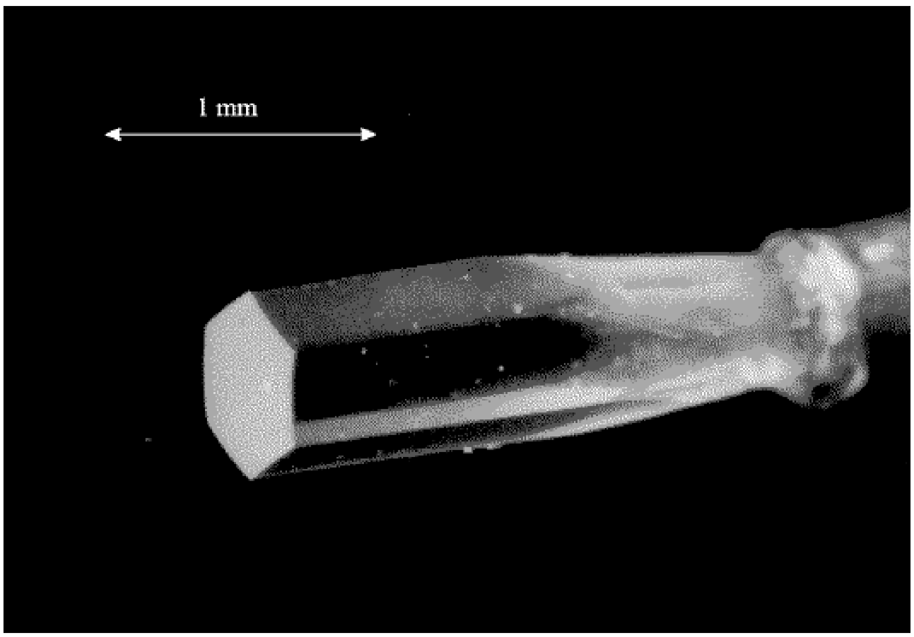

Figure 2. Flared fiber for cryogenic image-slicers: The image shows one of the lens-fiber units that are used to sample the image-plane. Each unit is built up from a silica-fiber, that has been flared to the form of a taper, and a spherical lens polished onto it.

Like the fiber-solution, the third concept for integral-field-spectroscopy is based on a micro-lens-array in the image plane. But instead of reimaging the pupil of the individual lenses onto different fibers, the whole set of micro-pupils is now fed into a spectrograph.[1] With the micro-pupils filling only a small fraction of the total field, with a slight tilt in the dispersion direction the spectra on the detector fill the unused detector area between the micro-pupils without overlapping of the individual spectra. Compared to the fiber-based concept, there is no additional loss of light due to the coupling of light into the fiber. Also the technology of producing micro-lens-arrays is now well established, and its application in cryogenic instruments seems straight forward. But while both mirror- and fiber-slicers can disperse the light all across the detector, the spectra of the micro-pupils need to be truncated before they overlap with the spectra of another micro-pupil. Therefore such instruments can provide high spectral resolution only for a very limited wavelength range.

2.2. Multi-Object-Spectroscopy

The need for multi-object-spectroscopy is obvious for faint object astronomy. Whenever good statistics is crucial for the scientific interpretation, we need to have information on as many objects as possible. And since many programs require integration times of several hours per object, simultaneous observations of a large number of objects are the only possibility to carry out the observations within a reasonable time.

There are two basic concepts to carry out simultaneous spectroscopy of multiple objects in a field: Using multiple slits and coupling the light into fibers.

In the multi-slit approach a mask with slits located at the object positions is placed in the image-plane. This slit-plate is normally fabricated "off-line" prior to the observation. Special care must be taken to avoid overlap of the spectra from different slits. Therefore usually several masks and observations are required for a complete set of spectra of the objects within a given field. The big advantage of such slit-mask-spectrographs is their high optical throughput, since no additional optical element is introduced. Examples for such instruments are the CFHT MOS[6] and the two VIRMOS[7] instruments for the VLT. One way to overcome the "off-line-production" of the slit-masks might be with micro-mirror arrays which would allow electronically controlled object selection.

The second concept of multi-object-spectroscopy is based on fibers. While in previous instruments fibers had to be placed by hand, nowadays robots arrange the fibers, like in the AAT 2dF.[14] Depending on the image-scale and the f-number, the light is either coupled directly into the fiber, or a lenslet is used to reimage the telescope-pupil onto the fiber core. As the fiber-based integral-field-unit, such multi-object-spectrographs can be expanded to almost any number of objects.

For the time being, no cryogenic multi-object-spectrograph for the infrared wavelength range has been set into operation. For the LUCIFER instrument for the LBT, however, possible realization of the two concepts — multi-slit and fiber-based — in a cryogenic instrument are under study: In a multi-slit-spectrograph, the technical key-problem is that the slit-masks have to be produced "off-line", and need to be inserted into the cryogenic system. One possibility would be an air-lock through which a set of slit-masks are fed into a juke-box and cooled down to the temperature of liquid nitrogen, before they are actually moved into the field. A fiber-based system, however, will require a fully cryogenic robot to position the fibers. But unlike their optical counterparts, present-day fibers for the infrared are either rather fragile (zirconiumflouride), or show significant extinction towards longer wavelengths (waterfree silica). Therefore long fibers and big movements should be avoided, and a "Spaltspinne"-like[12] mount of the fibers with a long-slit-spectrograph located directly behind seems most promising. While the fiber-technology — e.g. based on the monolithic concept described for the integral-field-unit — is almost established, a reliable cryogenic robot is not yet in operation.

A common problem to both multi-object-concepts described above is the need to have precise target positions. In addition no (fiber-concept) or very limited (multi-slit, since all slits are parallel) spatial information can be obtained.

2.3. Multi-Field-Spectroscopy

Both problems of multi-object-spectrographs — the need for precise target-positions, and the lack of spatial information — will be overcome by multi-field-spectroscopy: Like in multi-object-spectrographs, multiple objects are observed simultaneously, but now each object is spatially sampled with an integral-field-unit.

In principle each of the three basic concepts for integral-field-units — mirror-slicer, fiber-slicer, or micro-pupil-array — could be combined with the multi-object concept:

Little mirror-slicers or micro-pupil-arrays are the natural extension of the slit-mask (figure 3). Assuming the same pixel-scale, the same size of the individual fields and the same size of the detector, the source density decides which slicer-concept matches best the science-program. For micro-pupil-arrays, all the objects should be within a field with a linear dimension equal to the number of fields times the size of each single field. For mirror-slicers, the objects should be arranged more loosely, the objects at least separated by the square of the linear dimension of each subfield.

Most promising, however, is the combination of the fiber-based multi-object- and integral-field-concepts. The single fibers of the multi-object-spectrograph need only to be replaced by small fiber-slicers built from several lenslet-fiber-units (figure 4). Depending on the science-program, either small individual fields with about seven pixels each, or larger fields with about 100 spatial elements would be selected. The monolithic concept developed for the fiber-slicer as described above would fulfill all requirements for this kind of multi-field-spectroscopy.

However, like multi-field-spectrographs based on fibers, all multi-field-solutions for the infrared wavelength-range require reliable cryogenic robots.

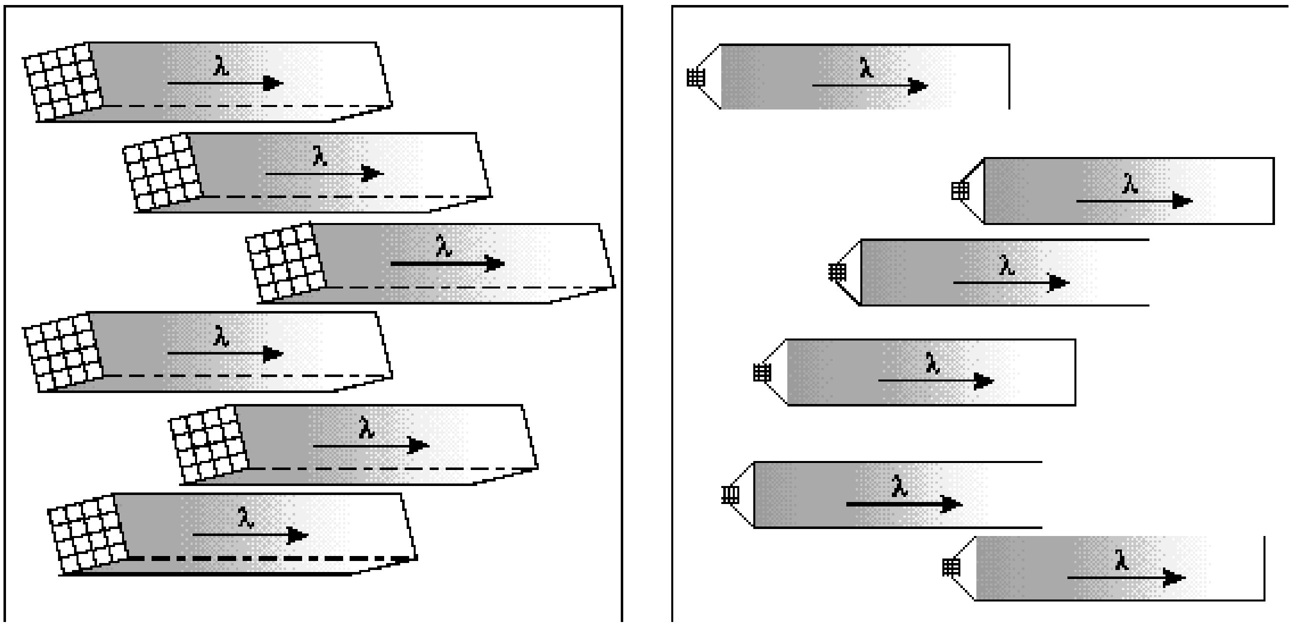

Figure 3. Mulit-field-spectroscopy with micro-pupil-arrays (left) and multi-mirror-slicers (right) is the natural extension of the slit-mask concept. Which slicer concept matches best the science-program depends on the source density in the field. Please note that in both drawings the size of the individual fields and pixels are the same. The relative separation of the individual fields, however, is much larger for the mirror-slicer concept.

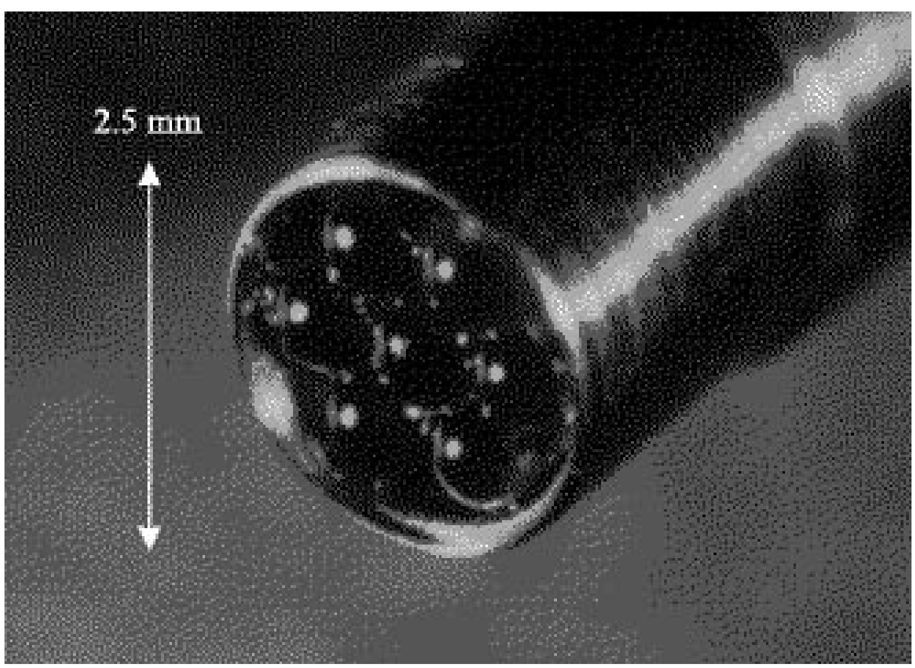

Figure 4. Mulit-field-spectroscopy with fibers: The monolithic lens-fiber-units of figure 2 can be arranged in any form. This image shows the building block of a possible multi-field-spectrograph that provides seven image points per object.

3. Comparison

3.1. General Considerations for Extremely Large Telescopes

Before comparing integral-field-, multi-object-, and multi-field-spectroscopy for extremely large telescopes, we discuss the noise regime and pixel-scales for such instruments.

What is the maximum pixel scale? In order to get a rough estimate, we will assume a telescope with a diameter of 100 m. The physical size of a pixel of a present day near-infrared-detector is about 20 μm. We further know from present-day near-infrared-instruments like SPIFFI[16] that the f-number of any camera-optic needs to be greater than or equal to roughly 1 to achieve acceptable image quality. From this limit, and the fact that $A\Omega$ is preserved in imaging optics, one can derive a maximum pixel size of 60 mas. So whenever larger image elements are required, their flux must be spread over several pixels. The smallest pixel scale is determined by the diffraction limit of the telescope. For the H-band (1.65 μm) the appropriate pixel scale to Nyquist-sample the image is 3 mas.

What is the noise regime we have to work with? Let us assume H-band observations again. Most of the sky-background in this wavelength range arises from about 70 OH lines,[8,11] which sum up to a total surface brightness of about 14 mag / arcsec^2. The flux between the OH-lines is roughly 18 mag / arcsec^2. The first lesson we learn from these numbers is that even for present day technology OH-suppression is crucial for deep observations. In order to loose only 1/10 of the H-band-spectrum to OH-contaminated pixels, roughly 1400 pixels are required for Nyquist-sampling, corresponding to a spectral resolution of approximately 3000 in H-band. But even at this spectral resolution and with adaptive-optics-pixel-scales, observations will be background-limited assuming future detectors with a read-noise close to 1 electron and negligible dark-current, and integration-times of the order of 1 hour.

3.2. What concept is best suited for extremely large telescopes?

Extremely large telescopes provide the unprecedented opportunity for spectroscopy of (a) extremely small and (b) extremely faint objects.

For us it is obvious that spectroscopy at the diffraction limit of an adaptive-optics equipped telescope and with pixel scales of the order of milliarcseconds requires integral-field-units. Of the three concepts described above — mirror-slicer, fiber-slicer, micro-pupil-array —, the mirror-slicer provides the most efficient use of detector elements, because it is the only technology that actually uses almost all pixels. Being not yet at its limitation in field-coverage, this concept may be the choice for the next generation of instruments. In the more distant future, when detector-size and -availability will not limit our instrumentation-plans any more, the micro-pupil-concept, and finally the most expandable fiber-concept are most appropriate.

Since we will be sky-limited at near-infrared-wavelengths at any pixel-scale, the biggest gain in sensitivity (5 magnitudes) over 10m-class telescopes will be achieved by adaptive-optics-assisted observations of point-like sources. In order to make most efficient use of the telescope time, multi-object spectroscopy will be one of the most important operation modes for extremely large telescopes. But with the pixel-size of a few milliarcseconds, the problem of accurate slit-positioning will require the extension of the multi-object-technique towards the multi-field-approach. For this application the fiber-based-concept combined with a cryogenic robot seems most promising.

For spectroscopic surveys the object-density will finally determine the most appropriate instrumentation. But one should keep in mind that — in contrast to smaller but equally sensitive future space-telescopes — the maximum pixel-size for a 100m telescope will be limited to about 50 mas. Assuming OH-suppressed observations in the H-band with roughly 1400 spectral pixels for each image point, even 16 detectors with 4k $\times$ 4k pixels could only cover a field 20 arcsec on a side. In order to make efficient use of an integral-field-unit for this application, the source density should be of the order 10^4 objects per arcminute, like extragalactic star-forming regions. For most applications, however, the source density will be much smaller, and the combination of deep imaging and multi-field-spectroscopy will match best.

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